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DIAMOND MACHINING AND MECHANICAL INSPECTION OF OPTICAL COMPONENTS

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DIAMOND MACHINING AND MECHANICAL INSPECTION OF OPTICAL COMPONENTS

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Abstract

Displacement measurement and motion control are discussed for rotary and linear axes of motion, as necessary for the dimensional measurement and diamond-tool machining of grazing incidence x-ray optics. Examples of available performance levels are drawn from measurements made on current developmental hardware, and are coupled with speculation on possible future extensions.

Introduction

The aim of this paper is to describe current developments in the area of precision engineering that may be of interest for soft x-ray optics operating at grazing incidence. These will include both diamond-tool machining and dimensional metrology examples. A central theme in the following discussion is the measurement and control of the axes of the machine tool or measuring machine.

Our efforts have not been specifically directed at the field of x-ray optics, and hence the work to be described is of more generic than immediate interest. However, examples of both x-ray microscopes[1] and Wolter-type EUV telescopes[2] have been diamond turned at LLNL.

Due to the extreme edge sharpness and clean cutting ability of diamond tools with certain materials, very fine finish cuts (0.1-1.0 μm) are possible, with consequent low cutting forces (1 gr. or less). Therefore the design distinctions between a diamond turning machine and a coordinate measuring machine are relatively minor; indeed, many existing diamond turning machines have been constructed around commercial measuring machines.[3] Since the technical problems of a coordinate measuring machine are for the most part a subset of those for a diamond-tool machine, we will discuss the measuring machine problem first, followed by additional comments on diamond machining.

Roundness Measurement - Compuron

The simplest example of a coordinate measuring machine is a roundness instrument, which measures only the radial deviations of the workpiece surface from an axis of rotation (at, in general, an arbitrary polar angle). By the same token, the instrument is most easily carried to a high level of accuracy, and hence represents a useful reference point.

Fig. 1 shows a schematic diagram of the LLNL "Compuron," so named because of its microcomputer-based data acquisition system. The measurements consist of the rotation angle, with 4096 steps per revolution, and the gagehead reading. The latter is an analog signal from a linear variable differential transformer (LVDT), digitized to a resolution of 2.5 Å (0.01 μin.). The microcomputer provides selectable digital filtering, multiple revolution averaging, removal of centering error by a least-squares routine, determination of p-v (peak-to-valley) and rms roundness error and a frequency domain (cycles/revolution) transformation through an FFT routine.

A crucial consideration in the measurement of roundness is the separation of the error motion of the instrument spindle from the nonroundness of the object being measured, the sum being present in a single measurement. This separation can be accomplished rather simply and elegantly by a 180° reversal method, in which the gagehead and object are indexed one-half revolution to provide the difference signal of the two error components.[4] Once separated, the spindle error motion can be stored in the microcomputer and subtracted from subsequent measurements.

The accuracy of the reversal method (and of the subsequent subtraction of spindle error) is limited by the repeatability of the spindle and measurement system from revolution to revolution. Aerostatic spindles are used less for their high inherent accuracy than for their even higher repeatability. Fig. 2 shows a Compuron repeatability measurement consisting of the difference between two 16-revolution averages with a 40 cycle/rev cutoff taken approximately one-half hour apart. The maximum p-v amplitude is 12.5 Å (0.05 μin.) with an rms value of 2.5 Å (0.01 μin.). For the same averaging and cutoff values, the

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overall system roundness measurement accuracy has been established at 25 Å (0.1 μin.) p-v. (For comparison, the repeatable spindle radial error motion is approximately a factor of ten larger).

Fig. 3 shows the details of the gagehead and mount. Measurement is made by direct contact of a diamond-tipped stylus against the workpiece. The stylus shaft is floated on a porous graphite aerostatic bearing, eliminating Coulomb friction. An adjustable back-pressure feature permits a contact force as low as 0.1 gr., independent of stylus travel.[5]

The choice of a contact or non-contact gaging technique often elicits strong viewpoints. The contact method clearly has the potential for wear and surface damage, which is avoided (or at least held to an acceptable level) in the above example by use of a diamond tip and a low force. Bennett has carried this approach to the extreme of a 0.1 x 2.5 μm hatchet stylus on very soft materials[6], but smooth surfaces and very low ambient vibration levels are required to avoid stylus hopping. Lateral resolution requirements are one basis for selection, with an increasing sequence running from the contact stylus to a focused laser beam (as in the Sommargren optical profilometer[7]) to capacitance sensors. In principle, any of these could be employed for the above purpose.

While the performance of the Compuron is adequate for many tasks, potential for improvement remains. The tests to date have been conducted in a poor thermal environment, where transient and variable differential expansion effects could alter the spindle housing shape and hence the error motion. The ambient vibration level was also higher than desirable. If all external influences were removed, the present electronic noise level of 15 Å (0.06 μin.) p-v in a 10 Hz bandwidth[8] would give a 16-revolution value of 4 Å (0.015 μin.) p-v (assuming $N^{1/2}$ averaging), about a factor of three improvement over the results quoted above. Since our LVDT electronics design is operating within a factor of two of its Johnson noise limit, significant gains would be more readily obtained by another technique. Radically higher sensitivities are possible. For example, Moss et al[9] have shown a sensitivity of 1.3 x 10^{-4} Å/$\mathrm{Hz}^{1/2}$ in a laser interferometer, and Jones[10] quotes an rms noise level of 5 x 10^{-5} Å/$\mathrm{Hz}^{1/2}$ using a differential capacitance gage. A smaller resolution than 2.5 Å in the A/D converter would, of course, be required if significant gains were made.

Regarding transducer accuracy, it should be noted that a dynamic range in excess of 10^3 is difficult to obtain in an analog device. For example, a 0.1% LVDT nonlinearity coupled with a 2.5 μm (100 μin.) centering error signal could distort the Compuron roundness measurement by 2.5 Å (0.1 μin.).

The Compuron is sized for objects up to 35 cm (14 in.) in length and diameter and 270 Kg (600 lb) in weight. There is no obvious scaling effect to suggest that roundness measurement should become less accurate as the instrument or object diameter increases (in contrast to, say, length measurement), although greater attention must clearly be given to structural stiffness and thermal stability.

Cylindrical Coordinate Measurement - LODTM

To fully measure an axisymmetric grazing incidence device, the gagehead stylus tip (or its noncontact equivalent) from the roundness instrument example must be translated along a curvilinear path in a vertical plane containing the centerline. This greatly expands the problem, typically requiring two orthogonal linear axes with length-measuring systems and servo drives coordinated by a control system.

Fig. 4 shows a current high-technology effort in this category, known as the Large Optics Diamond Turning Machine (LODTM). The motiviation for this machine is the diamond turning of reflective optics for high-energy lasers. The machine is being designed and constructed by LLNL with funds from the Defense Advanced Research Projects Agency, monitored by the Air Force Wright Aeronautical Laboratory. The size capacity will be 1.62 m diameter by 0.5 m axial length. While designed as a machine tool, LODTM can (and will) be used as a cylindrical coordinate measuring machine. The latter use will be assumed for the present discussion.

The 40-month LODTM Project is at its midpoint as of this writing, and hence the machine is not complete. However, several critical subsystems of interest for the present discussion have been tested in prototype form, and are discussed in the following sections.

Axis Displacement Measurement System

The axis displacements are measured with laser interferometers. The stationary interferometer components are attached to a "metrology frame," a reference structure that is kinematically supported from the main frame and is kept free of variable loads. The beam paths are enclosed in evacuated welded metal bellows with windows at the outboard ends. After traversing a 1 mm air gap, the beams are reflected from optical straightedges. Fig. 5

shows the overall arrangement; multiple interferometers are used to provide symmetry and to allow position extrapolation to the tool gagehead location in the presence of angular motion of the carriage or toolbar. Note that the measurement scheme automatically accounts for slideway straightness errors; straightedge error will be calibrated in place and stored in look-up tables in the control computer.

As a result of the long travel, the laser wavelength must be carefully controlled to achieve the desired position stability. The laser source used for all interferometers is a moderate power (5-10 mW) He-Ne unit which is frequency offset locked to a low power (80 μW) Iodine-stabilized He-Ne laser of NBS design.[11] The source laser beam is passed through a Twyman-Green interferometer constructed with polarizing beam splitters, and containing a Bragg cell frequency shifter in each arm. The frequency shifters are driven with a 1.75 MHz difference frequency, resulting in the production of an output beam with linear polarization components suitable for heterodyne interferometry.[12]

The interferometers used in each measurement leg consist of a polarizing beam splitter, two corner cubes and a quarter wave plate arranged to cause the beam to traverse the measurement leg four times. The resulting resolution of 1582 Å (6.2 μin.) per fringe is further extended by a digital phase interpolation to yield a signal with a resolution of 6.2 Å (.024 μin.) per bit.[13] This high resolution is required so that sums of individual measurements used to calculate the toolbar position will contain a quantization error smaller than the 25 Å (0.1 μin.) control system resolution.

An error analysis of the interferometers, including experimental measurements of component performance and estimation of stress-birefringence resulting from atmospheric pressure loads, yields an upper bound of 20 Å (0.08 μin.) on the p-v error. This error bound is dominated by a periodic error resulting from undesired mixing of the two polarization components due to imperfect polarizer performance and material birefringence. This error amounts to a few parts in 10^9 over the distances involved, and in our esimation would be difficult to improve significantly without abandoning the use of commercial optical components.

Axis Motion Control System

The LODTM axis drives are traction type, in which a smooth roller is preloaded against a smooth flat bar, so that lateral shear stress provides a rack-and-pinion effect without the drawbacks of gear teeth. The roller is supported by hydrostatic bearings and carries an integral dc torque motor and tachometer. This arrangement provides a smooth, low-friction drive with high resonant frequencies. Its major drawback is the very low mechanical gain; a 5 cm (2 in.) diameter roller provides 250 Å (1 μin.) of travel per microradian of motor rotation.

Fig. 6 shows a servo test-bed that was built to study the low-speed, high-resolution motor control required for such a drive. The housing at the rear contains the contact roller between a pair of hydrostatic bearings, with the motor and tachometer located above. Contact is made against the rear of the prismatic drive bar, which is flexure connected to a sled riding on aerostatic bearings. Position feedback is provided by a laser interferometer equipped with the resolution extension system described previously.

The position control loop was closed with a bandwidth of approximately 10 Hz using sled masses ranging from 200 to 500 pounds. Fig. 7 displays a typical position measurement for a 200 pound sled responding to a 0.1 Hz, 250 Å (1.0 μin.) p-v amplitude triangle wave command signal. Of particular note is the lack of discernible hysteresis at the turnaround points. Both the following error and the transient response measured with the test-bed[14] are consistent with a classical 10 Hz servo system. Controlability of the motion control system is better than 12 Å (.05 μin.), with slide position accuracy determined by the displacement measuring system.

Capacitance Gages

As indicated by Fig. 4, the LODTM metrology frame extends down to the spindle rotor, where capacitance gages are employed to sense axial, radial and tilt motion during spindle rotation. (Rotor shape errors are removed by the techniques described previously for the Compuron). The gages are double-sided for increased linearity and reduced sensitivity to ambient air dielectric variables.

The capacitance gages are differentially driven as elements in an ac bridge at a frequency higher than the desired measurement bandwidth.[15] The principle theoretical performance limits of the gages are the maximum air gap field strength (of order 10^3 V/inch) and the equivalent input noise of the first buffer amplifier (approximately 20 nV/Hz$^{1/2}$). This leads to a noise level limit of 20 x 10^{-12} in/Hz$^{1/2}$. A prototype sensor has been built and tested to determine linearity, noise and stability. The plate area used by the prototype, 0.1 in.^{2}, is an order of magnitude smaller than the actual gages will use. Nonlinearity of the gage has been determined to be less than 25 Å (0.1 μin.) in ±2.5 micron (±100 μin.) of travel. Noise was measured to be less than 0.6 Å/Hz$^{1/2}$ (2.5 x 10^{-9} inch/Hz$^{1/2}$). Drift of a fixed glass and copper capacitor was measured at less than 5 Å (.02 μin.) in 30 hours. In the case of the linearity and stability measurements, the error bounds are limited by the measurement technique, not the capacitance gage. No attempt was made to reach the limiting noise value; the measured noise is determined by electronic design of the capacitance gage buffer amplifier, which was chosen for robust performance at an acceptable noise level.

Temperature Control

Change of size and shape due to temperature variation can be a serious source of error for typical engineering materials. The workpiece must be isothermal at a known temperature (customarily 20°C). However, it can be seen that a measuring machine structure can be non-isothermal providing that the temperature field is time-invariant, and that this requirement applies only to the structural loop components comprising the dimensional measurement system between the workpiece and the gagehead. Thus, temperature control is part of the total measurement and control problem.

At LLNL, we have employed large recirculating flows of temperature-controlled liquid (water or oil) in numerous applications over the past fifteen years. The fact that the temperature is controlled only at the source output, and hence is open-loop across the machine structure, is nonetheless effective due to the high heat capacity of the liquid flow. For LODTM, examples are internal water passages adjacent to the spindle bearing surfaces and a double-walled water jacket that fully encloses the metrology frame (not shown in Fig. 4).

Since pump work, room lighting, etc. tend to heat the liquid flow, it is sufficient to control temperature by cooling only, using a shell-and-tube heat exchanger fed with chilled water. Fast response can be obtained by varying the chilled water flowrate and hence the convective film coefficient. We have previously demonstrated 0.005°K (0.01°F) p-v control in a 60 sec bandwidth for a 2.7 litre/sec (40 gpm) flowrate of light oil by a simple on-off control of chilled water flow via solenoid valves.[16] For LODTM, we have extended this approach by using a positive displacement pump driven by a servomotor with tachometer feedback for continuous chilled water flow regulation, and a proportional-plus-integral controller for better load-change rejection. Temperature sensing is done with commercial bead-in-glass thermistors. The same ac bridge used for the LODTM capacitance sensors is employed for high resolution, and has demonstrated 50 μ°K (10^{-4}°F) in a one-Hz bandwidth. Fig. 8 shows a 6.7 litre/sec (100 gpm) prototype unit. Fig. 9 gives the measured temperature at the heat exchanger exit and about 3 m (10 ft.) downstream during a 400W step change in heat load.[14] This performance is about a factor of ten better than for the earlier on-off control system under constant load.

If necessary, the above temperature control could be improved by using more sensors for better cross-stream averaging (the primary cause of control-point versus downstream differences in Fig. 10) and upstream "look-ahead" sensing in the two water streams. However, for common metals with expansion coefficients of order 10ppm/°K, the system described can hold thermal expansion to about five parts in 10^9. Especially for grazing incidence devices made of low-expansion materials, further improvement should not be needed.

Grazing Incidence Measuring Machine Concept

In speculating on a cylindrical coordinate measuring machine for grazing incidence optics, the problem can be simplified by considering the special geometry of Wolter-type devices, which are a fair approximation to a hollow cone with a few degrees of taper angle.

For microscope objectives, the sagitta height can be within the dynamic range of an analog transducer of high sensitivity (e.g., 2.5 μm sagitta height and 25 Å accuracy for a 10^3 dynamic range). Thus, adding a single linear slide axis to translate the gagehead of a roundness instrument provides the basic features. An axis measurement system is necessary, but the accuracy requirement is greatly reduced (by a multiplier approximately equal to four times the sagitta height over the microscope length). The straightness error of the slide must be repeatable to a value smaller than the desired figure measurement accuracy, and must have a p-v magnitude that does not cause the gagehead dynamic range to be exceeded. With repeatability, the slide strightness error can be measured against a reference straightedge and stored for subsequent corrections. A perfect straightedge is not required, since the same reversal concept used to separate spindle and object errors can be used to separate the slide and straightedge errors. If a radiused contact stylus is used, consideration must be given to the stylus tip roundness and cosine errors, both arising from the optical surface slope variation relative to the slide travel direction. Finally, adequately accurate values must be obtained for a) the angle between the direction of the slide travel and the microscope centerline and b) a diameter dimension at some known axial location. Given the need for at least one diameter measurement, it may be simplest to infer the angle from two diameters at opposite ends of the optic.

For larger x-ray telescope components, two factors may change. First, the sagitta height deviation from a cone may exceed a reasonable analog gagehead dynamic range. One possibility is to use a laser interferometer, either directly or as a measuring element behind a stylus follower. Another possibility is to note that end moments and lateral loads on a prismatic bar yield quadratic and cubic deflection terms which might be used to generate a curved slider path approximating the telescope shape within the dynamic range of an analog gagehead. The second factor is that the larger sizes and weights may lead to the need for a metrology frame concept analogous to the LODTM design.

Diamond Machining of Grazing Incidence Optics

General Discussion

In examining diamond machining versus conventional optical grinding and polishing techniques for x-ray optics fabrication, it is more appropriate to view the two methods as complimentary rather than as mutually exclusive alternatives. The largest drawback of diamond machining is the high local slope occurring at the shorter spatial wavelengths (surface finish regime). While rms amplitudes of a few tens of Angstroms can be achieved, the associated rms slopes can still be tens of milliradians.[17] On the other hand, diamond machining is attractive in its ability to produce aspheric optical figures to high accuracy. This contrasts with optical polishing, which can rapidly smooth the short-wavelength, low-amplitude finish errors but tends to degrade aspheric figure if continued for a longer period.[18] The grazing incidence optics fabricated at LLNL to date have all been diamond turned by our Metrology Group, followed with polishing by our Optics Group.[1,2]

A significant benefit of diamond turning is the ability to provide mounting and reference surfaces that are accurately aligned to the optical axis, which can simplify assembly procedures dramatically.

A limitation of diamond machining for x-ray applications is the limited range of materials that diamond will cut cleanly and with negligible tool wear. These include gold, silver, copper, aluminum, lead and their alloys, electroless nickel (with additional difficulty), but not including elements with high atomic number, glasses or ceramics such as ULE and Zerodur. A common technique is to plate a diamond machinable material onto another substrate, and in some cases to vapor-deposit a second thin layer of a harder material after diamond machining, to facilitate optical polishing.[2]

Returning to the subject of diamond-machined surface finish, it is easy to speculate that improvements might be made, simply because of a lack of basic understanding of the diamond tool cutting process. (Historically, the cutting process has been sufficiently ideal to stimulate the development of the entire diamond machining field, and has been neglected in comparison to the larger problems of reducing the various machine errors). It is observed, for example, that the surface roughness is significantly less along the machining grooves than across them, and also that the cross-groove roughness contains slopes that are large compared to those of the theoretical scallop-shape associated with the round tool nose.[19] Tool-to-work vibration that is asynchronous with spindle rotation is a contributor (and one that can be separately measured and diagnosed), but a small change in the method of application of a jet of cutting fluid is also known to change the roughness value.[20] This list of observations could be extended to great length, but would only emphasize our view that this subject could benefit from serious scientific study.

Based on the remarks of the preceding paragraph, it is interesting to speculate that x-ray grazing incidence optics might benefit from cutting in an axial rather than a circumferential direction. Such a machine would be similar in geometry to the grazing incidence measuring machine outlined previously. (In terms of the stroking motion, machining rate and stringent accuracy requirements, it would also bear a strong resemblance to a diffraction grating ruling engine).[21]

Diamond Machine Design Factors

It was noted earlier that coordinate measuring machines and diamond-tool machines have many features in common. Perhaps the most marked difference comes from the fidelilty of the diamond tool in transferring the error motions of the machine into the part surface in real time. For a measuring machine, high frequency vibration can be removed by filtering, and statistical uncertainty can be reduced by repeated measurement passes. Differences of this type lead to the need for higher bandwidth and lower axis position following errors for cutting machines than for measuring machines. An approach to this problem is presented in the following section.

LODTM Fast Tool Servo

The problem of improving bandwidth and reducing following error for a machine with the large slide masses of LODTM has been attacked by adding a short-travel, high bandwidth device named the Fast Tool Servo (FTS). A cross-section drawing is shown in Fig. 10. The tool holder is flexure-supported from a center post and is driven by a piezoelectric element, with position loop closure by a double-sided capacitance gage. The FTS resolution is 25 Å (0.1 μin.) and the total travel range is 2.5 μm (100 μin.) with a corner frequency of 100 Hz (a factor of ten above the main axis drives and a factor of ten below the laser interferometer and control system update rate). The FTS is mounted to the lower end of the vertical tool at a 45° angle, placing its relative tool motion outside of the main measurement system of Fig. 5. The FTS drive signal consists of the sum of the two main slide feedback loop position errors, resolved normal to the workpiece surface. (Because of the fixed 45° direction, a real-time multiplication of the two errors is made against programmed surface slope data by the control computer). We have not yet tested the design of Fig. 10. Brassboard tests have been made, using a commercial PZT and capacitance gage, to study the control loop difficulties arising from PZT hysteresis.[14] The tests showed that the error contribution due to hysteresis can be reduced below 3.5 Å (.014μin.) for 4 μm (160 μin.) total travel, and demonstrated a static compliance less than 2 μin./lb. Classical servo behavior with no detectable nonlinearities was obtained over a 100 Hz bandwidth.

When the LODTM is used as a measuring machine, the FTS can be replaced by a gagehead. By recording the FTS drive signal as well as the gagehead signal, correction for main slide dynamic position errors can also be made for measurements.

Summary

Current achievements in position measurement and position control for mechanical slideway motions ranging up to one meter (40 in.) indicate that coordinate measuring machines are a candidate for the inspection of grazing incidence x-ray optics. Specialized designs that capitalize on the specific geometry of the optics may simplify the task. The same technology could support the diamond-tool machining of these optics if issues such as material selection and surface finish improvement can be addressed adequately.

Acknowledgements

The authors are indebted to the members of the LODTM and Machine Tool Development staffs at LLNL for the designs and experimental results referenced here. Motion control and capacitance gaging results are the work of H. McCue, A. Maddux and D. Hopkins; temperature control results reflect the work of J. Roblee. D. Baird and H. Bissinger were instrumental in the analysis and measurement of the optical systems. The precision of roundness measurements quoted are in large part due to the skill of H. Hauschildt.

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21. The similarity might also extend to the air of quiet desperation over achieving satisfactory accuracy that is endemic to the ruling engine community. See Harrison, G. R., "The diffraction grating - an opinionated appraisal," Appl. Optics, Vol. 12, No. 9, 1973.

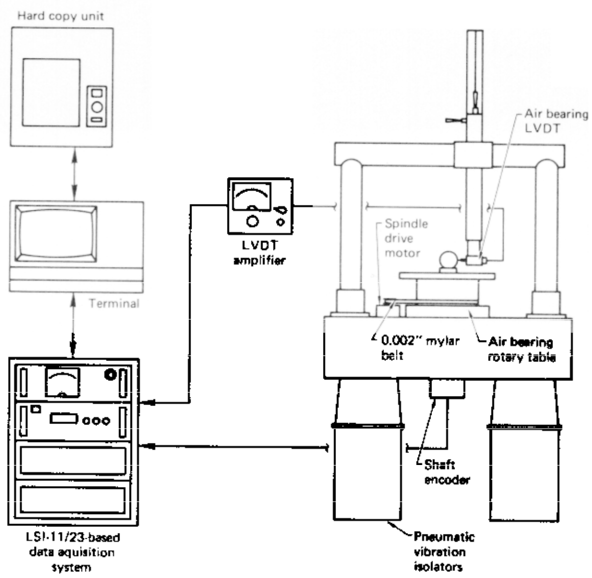

Fig. 1 Schematic of Compuron measuring instrument.

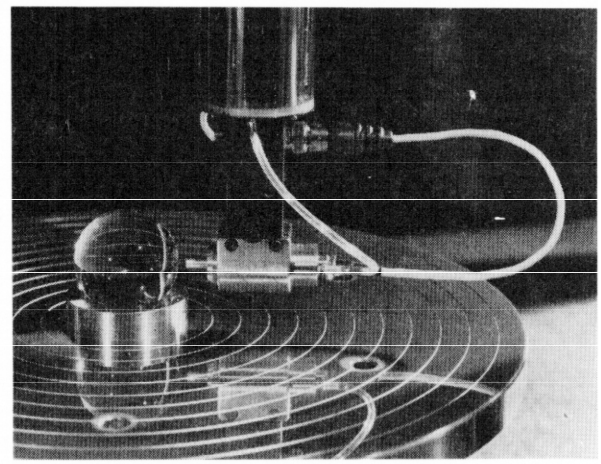

Fig. 3 Compuron with air-bearing LVDT gagehead and diamond-tip stylus.

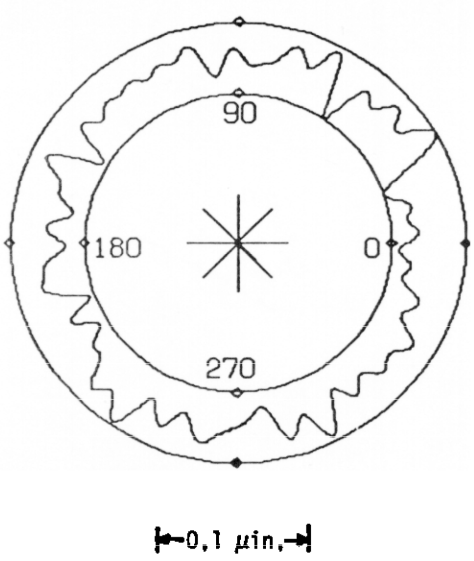

Fig. 2 Compuron repeatability measurement, 0.05 µin. p-v, 0.01 µin. rms. Difference of two 16-rev averages, 40 cycle/rev filter.

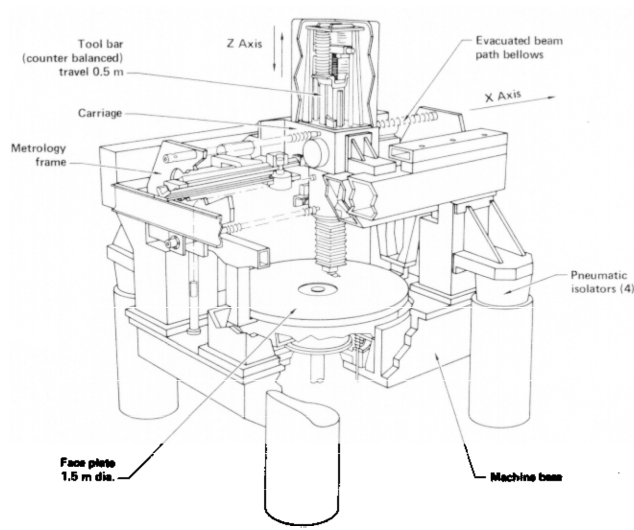

Fig. 4 Cutaway isometric view of Large Optics Diamond Turning Machine (LODTM).

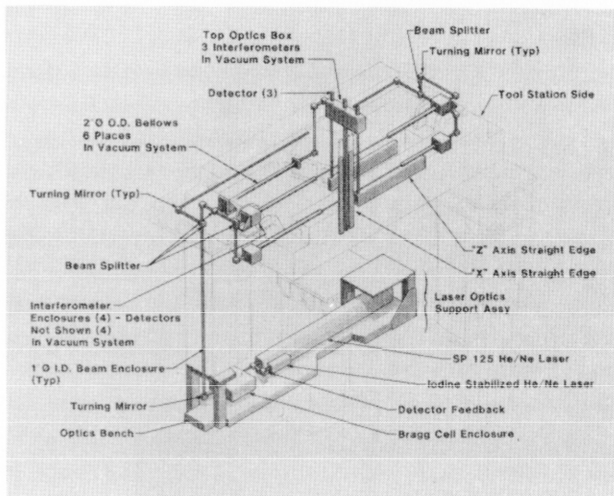

Fig. 5 LODTM axis position measurement system.

Fig. 6 LODTM traction drive servo test bed.

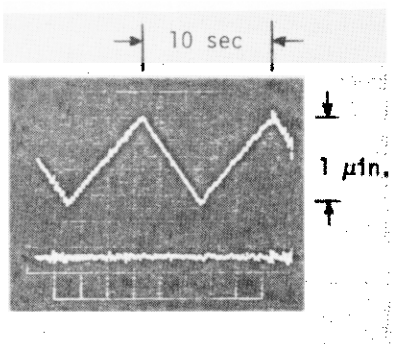

Fig. 7 Axis motion control system performance at low speed (one motor revolution per year). Upper trace is axis motion; lower trace is following error to same vertical scale.

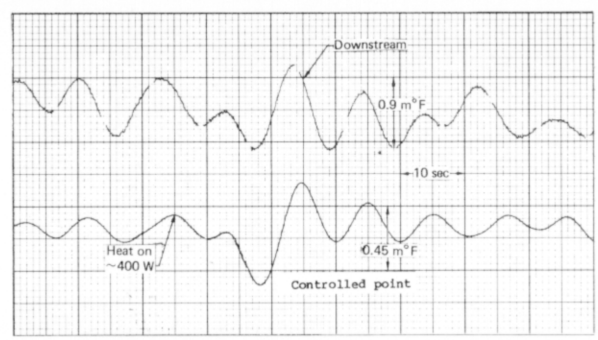

Fig. 9 Temperatures at control point and downstream point during a step change in heat load, using 0.01 Hz filter.

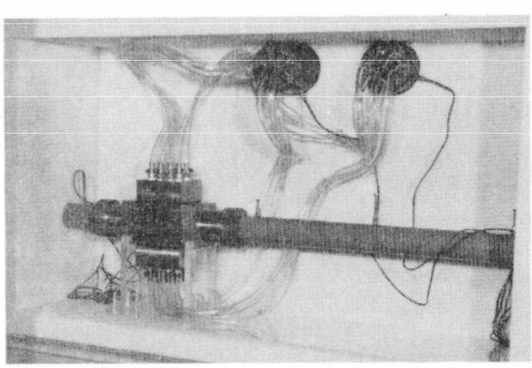

Fig. 8 Liquid temperature control experimental hardware.

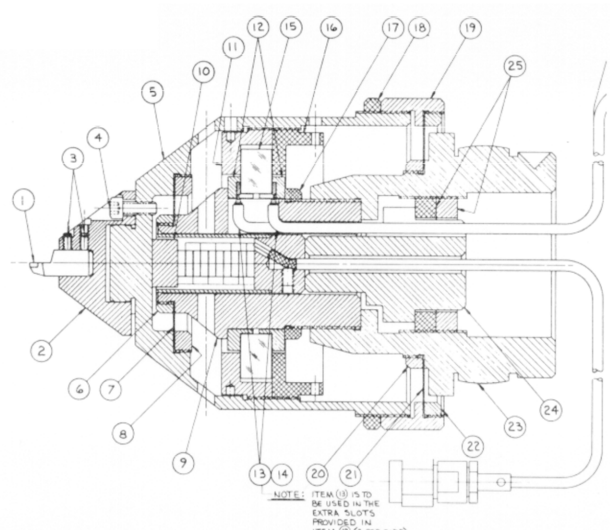

Fig. 10 LODTM fast tool servo cross-section.